

The Optical Fiber

- **Overview**

- **Fiber geometry**
- **Fiber parameters**
- **Confinement process**
- **Electromagnetic modes**
- **Step-index and graded-index fibers**
- **Multimode and single-mode fibers**

Optical Confinement

- Passing from high-index medium to low-index

$$-n = c/v \quad n_{\text{glass}} = 1.4 \rightarrow 1.5$$

- Snell's Law:

$$\theta_t = \sin^{-1} (n_1 \sin \theta_i / n_2)$$

- Critical angle

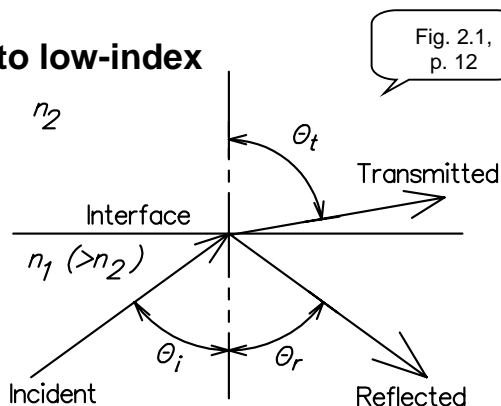
$$\theta_c = \sin^{-1} (n_2 / n_1) \quad (\theta_t \rightarrow 90^\circ)$$

- If **angle of incidence exceeds critical angle**, **total internal reflection...**

- » Light reflects at interface with **NO** loss
- » Light guided down fiber

- If **angle of incidence less than critical angle**, **partial reflection/ transmission...**

- » Light reflects at interface with loss
- » Light attenuates as propagates down fiber

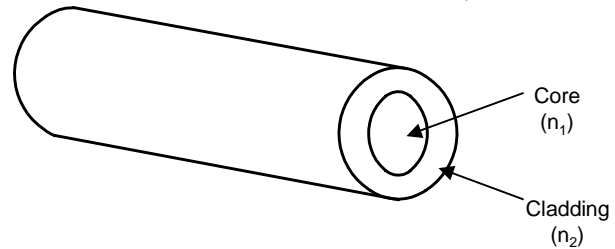


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Fiber Geometry & Step-Index Profile

- **Geometry (left)**

- **Core**
- **Cladding**
- **Buffer** (outside cladding)
- **Jacket**



- **Refractive-index profile**

- **Abrupt change at core-cladding interface**

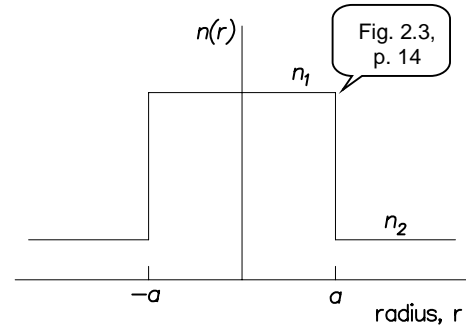
$$\Delta \equiv (n_1^2 - n_2^2) / 2n_1^2 \approx (n_1 - n_2) / 2n_1$$

$$n_2 = n_1 (1 - \Delta)$$

» Δ is “fractional change of n ”

» **Typical values of Δ :**

0.001 → 0.02 (i.e., 0.1% to 2%)



Fiber-3

Representative Fiber Parameter Values

Table 2.1,
p.14

Type	Core diam μm	Fiber diam μm	Δ
8/125 SM	8	125	0.1-0.2%
50/125 MM	50	125	1-2%
62.5/125 MM	62.5	125	1-2%
100/140 MM	100	140	1-2%

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Step Index (SI) Fibers: Waveguide Modes

- Cylindrically-symmetric dielectric waveguides
- Model and solve for the electromagnetic fields
- Certain characteristic electromagnetic **modes** can propagate
 - Simplest modes
 - » Modes with radial symmetry
 - » TE (transverse electric) and TM (transverse magnetic)
 - Hybrid modes also exist
 - » Combinations of TE and TM
 - » HM_{mn} and EH_{mn} modes
 - Linearly polarized
 - » LP_{mn} modes
- Each mode has its own propagation constant (i.e., velocity)

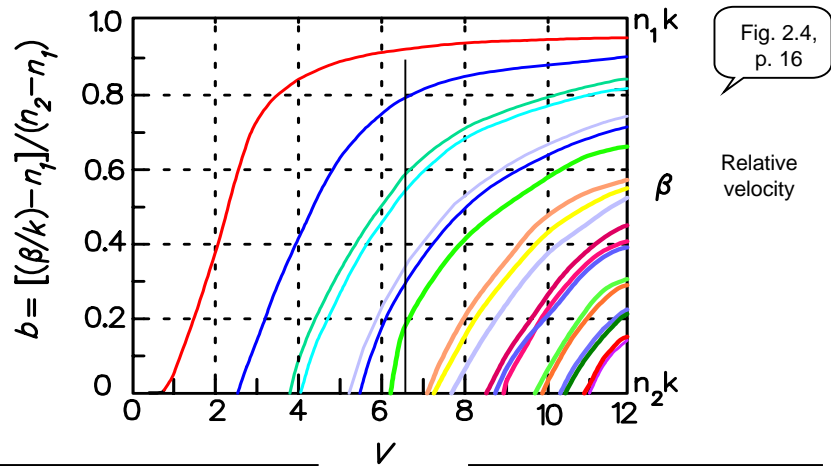
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Mode Behavior

- Fiber **V-parameter**:

$$V = (2\pi a/\lambda) \sqrt{n_1^2 - n_2^2} \approx (2\pi a/\lambda) n_1 \sqrt{2\Delta}$$

- Each mode has own velocity



- $V < 2.405$

- Single mode exists
- **Single-mode fiber**

- $V > 2.405$

- Many modes exists
- **Multimode fiber**
- Usually, $V \gg 2.405$

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Multimode Step-Index Fibers

• **Number of modes:** $N \approx V^2/2 \approx (2\pi a n_1/\lambda)^2 \Delta$ ($V \gg 2.405$)

• **Ray representation of multiple modes**

– High-order modes: Steep incidence (close to θ_c)

– Low-order modes: Low grazing angles

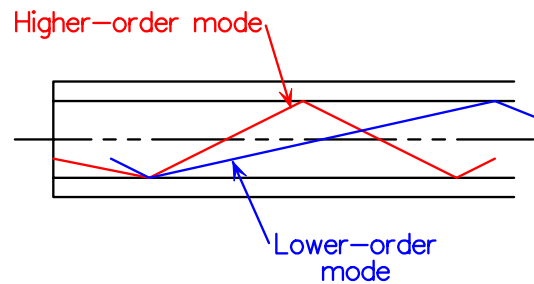


Fig. 2.5
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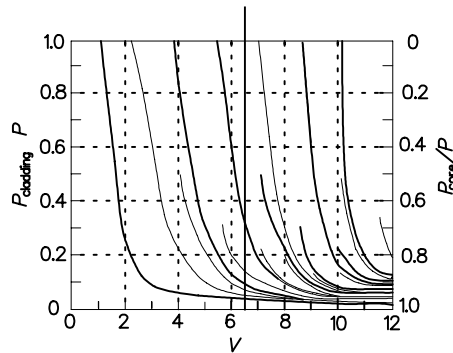
– Ray picture *not* appropriate for few modes or single mode

• Mode coupling (*mode mixing*) possible due to interface inhomogeneities

• Measurements of multimode phenomena require **uniform excitation of all modes**

Power Distribution Between Core and Cladding

- Cladding field **not** zero!
 - Mode's power carried in *both* core and cladding



- Fraction of total optical power in cladding:

$$P_{\text{cladding}}/P = 4/3\sqrt{N} \quad (V \gg 2.405)$$

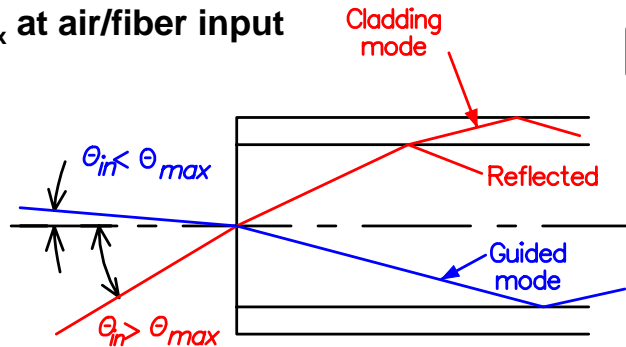
(*N*: number of modes)

- For small *V*, large fraction of power in cladding; **avoid this! (Keep $V \geq 2.0$)**

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SI Fibers: Numerical Aperture (NA)

- Coupling light into fiber
 - Only certain rays are accepted by fiber
 - Ray at θ_c at core/cladding interface...
 - ...is at θ_{\max} at air/fiber input



- Input rays...
 - **Less than θ_{\max} are guided**
 - **Greater than θ_{\max} , are not guided**

- **Numerical aperture:**

$$NA = \sin \theta_{\max} = \sqrt{n_1^2 - n_2^2} \approx n_1 \sqrt{2\Delta}$$

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Cladding Modes and Leaky Modes

- **Cladding modes:**

- Light carried in cladding
- Remove with **mode stripper**

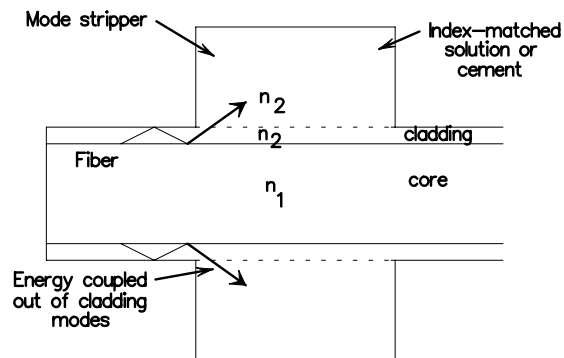


Fig. 2.8,
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- **Leaky mode:**

- Nonpropagating mode with power shared between core and cladding
- Difficult to predict and model
- Short-distance links can carry significant power in unguided modes and cladding

Step-Index Single-Mode (SI-SM) Fibers

- For $V < 2.405$
 - Only one mode propagates \Rightarrow *single-mode fiber*
- Generally,
 - **Small core radius** (2 to 5 μm)
 - **Small Δ** (typically, $<1\%$)
- Superior performance (over multimode fibers) for carrying high data-rate signals
 - *The fiber of choice!*

SM Fibers: Cutoff Wavelength and Power Distribution

- **Cutoff wavelength** (theoretical)

- V is function of λ
- Value of λ that makes $V = 2.405$
(step index fiber)

$$V_{\text{cutoff SI}} = 2.405 = \frac{2\pi a n_1}{\lambda_{\text{cutoff}}} \sqrt{2\Delta}$$
$$\Rightarrow \lambda_{\text{cutoff}} = \frac{2\pi a n_1}{2.405} \sqrt{2\Delta}$$

- Actual cutoff wavelength
 - » Susceptible to variations in fiber parameters
 - » Usually measured

- **Power distribution**

- At $V = 2.405$: $\approx 84\%$ of mode's power in core
- At $V = 1$: $\approx 30\%$ in core (power at risk of being lost)
- Do not want V too small
 - » Design compromise:

$$2.0 < V_{\text{SM SI}} < 2.405$$

SM Fibers: Mode Field Diameter

- Wave in SM fiber
 - Ray model *not* appropriate
 - Assumed mode in 1970s and 1980s: Gaussian shaped
 - » Modern fiber fields *not* Gaussian shape
 - Part of wave in core; part in cladding
 - » *a* does not describe “width” of wave

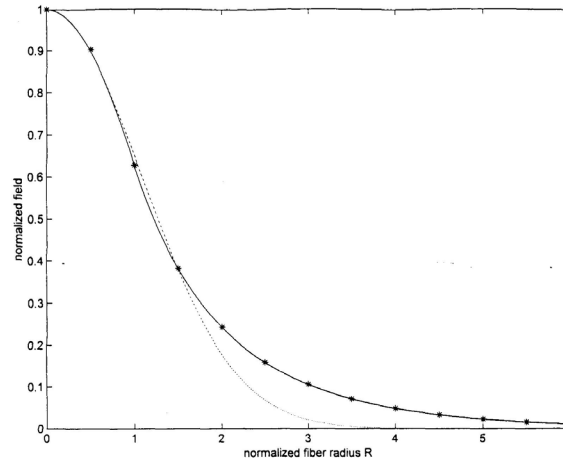


Fig. 7. Normalized field distributions for a step-index fiber at $V = 1.45$ ($V/V_{c0} \approx 0.6$); solid-line: *exact* field; dashed-line: Gaussian approximation; stars: proposed (two-parameter) approximation.

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SM Fibers: Mode Field Diameter

- ***Mode field diameter (MFD):***

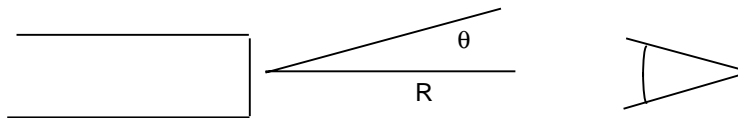
- Useful measure of field width
- Unfortunately, mathematically defined several ways

- **MFD used to predict...**

- Coupling losses
- Splice losses
- Connector losses
- Propagation effects
- Other effects in SM fibers

SM Fibers: MFD Definitions

- Circular fiber geometries assumed
- Measure field distributions
 - *Near-field optical amplitude distribution, $e(r)$*
 - *Far-field amplitude distribution $E(\rho)$*
 - » $\rho = 2\pi \sin \theta / \lambda$
 - Distributions are mathematically interrelated by the Hankel transform
- $|e(r)|^2$ and $|E(\rho)|^2$ are light *intensity* distributions
- MFD defined from measurement of **near-field** or **far-field intensity patterns**



SM Fibers: MFD Definitions (cont.)

- **MFD I: Near-field MFD** (or *Petermann I MFD*) :

$$d_n = 2\sqrt{2} \sqrt{\frac{\int_0^\infty e^2(r) r^3 dr}{\int_0^\infty e^2(r) r dr}}$$

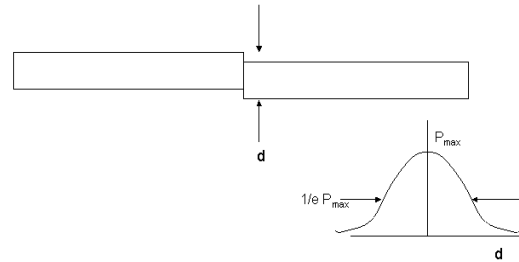
- **MFD II: Far-field MFD** (or *Petermann II MFD*) :

– Adopted as international standard

$$d_f = 2\sqrt{2} \sqrt{\frac{\int_0^\infty E^2(\rho) \rho d\rho}{\int_0^\infty E^2(\rho) \rho^3 d\rho}}$$

- **MFD III: Transverse-offset MFD**

- Growing out of favor, but easy to measure
- Two identical butt-coupled single-mode fibers
- Laterally displace one; measure transmitted power
- MFD (d_a) = offset when power is $1/e$ times initial power



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Multi-Step Single-Mode Fibers

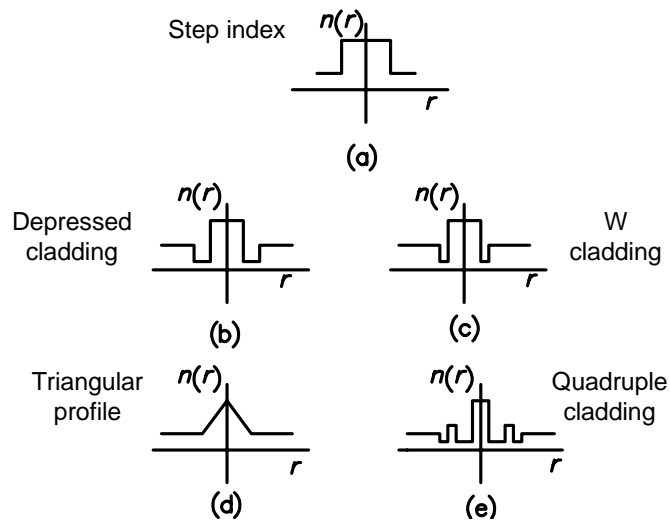


Fig. 2.9
p. 26

- **Pros:** increased data rates, less loss susceptibility, more fiber design flexibility
- **Cons:** harder to fabricate, harder to model

Graded-Index Multimode (GI MM) Fibers

- Non-step-index profile $n(r)$

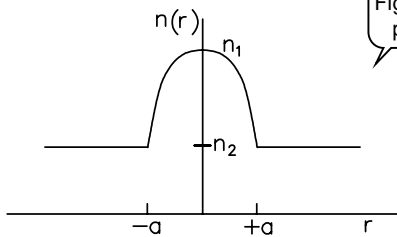


Fig. 2.10
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- Wave confinement by sinusoidal path within core

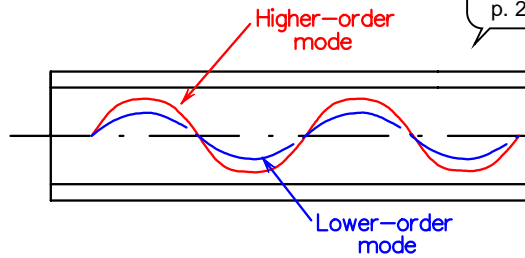


Fig. 2.11
p. 27

$$n(r) = \begin{cases} n_1 \sqrt{1 - 2\Delta (r/a)^2} & r < a \\ n_1 \sqrt{1 - 2\Delta} \approx n_1 (1 - \Delta) = n_2 & r \geq a \end{cases}$$

- Cladding

- Only isolates core from outside world
- No guiding action

Graded-Index Profiles

• Power-law profile model...

$$n(r) = \begin{cases} n_1 \sqrt{1 - 2\Delta (r/a)^g} & r < a \\ n_1 \sqrt{1 - 2\Delta} \approx n_1 (1 - \Delta) = n_2 & r \geq a \end{cases}$$

- n_1 : refractive index at core center
- n_2 : refractive index at core edge and in cladding
- Δ : fractional change in index (core center to edge)

$$\Delta = (n_1^2 - n_2^2) / 2n_1^2 \approx (n_1 - n_2) / n_1$$

» Same definition as SI

» $\Delta \approx 1\%$ to 2%

• Profile parameter or gradient, g

- $g = 2$: **parabolic profile** (Close to optimum for max data rate)
- $g = 1$: **triangular profile**
- $g = \infty$: **step-index profile**

GI Fibers: Number of Modes and NA

- **V-parameter** (for typically small Δ):

$$V \approx (2\pi a n_1 / \lambda) \sqrt{2\Delta} \quad (\text{same as SI})$$

- **Number of modes N :**

$$N_{\text{GI}} \approx \left(\frac{4\pi^2 a^2 n_1^2 \Delta}{\lambda^2} \right) \left(\frac{g}{g+2} \right) = \left(\frac{V^2}{2} \right) \left(\frac{g}{g+2} \right) = N_{\text{SI}} \left(\frac{g}{g+2} \right)$$

- **Numerical aperture**

- GI fiber NA more difficult to define than SI fiber NA
- Maximum acceptance angle θ_{max} is function of radial position of ray entry location.

- **Local NA:**

$$\text{NA}(r) = \begin{cases} \text{NA}(0) \sqrt{1 - (r/a)^g} & r < a \\ 0 & r \geq a \end{cases}$$

- » **NA(0): NA at core center**

$$\text{NA}(0) = \sqrt{n_1^2 - n_2^2}$$

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Single-Mode Graded-Index (SM-GI) Fibers

- Can make SM-GI fibers
 - Triangle profile
 - Parabolic profile
- Cutoff wavelength location: $V_{\text{cutoff}} = 2.405\sqrt{1 + (2/g)}$
 - Estimate:
 - » V_{cutoff} (triangle) = 4.38
 - » V_{cutoff} (parabolic) = 3.53
- All else being equal...
 - Core diameter of GI-SM fiber can be $\sqrt{1 + (2/g)}$ larger than SI-SM fiber
 - » Easier coupling
 - » Easier splicing
 - » Lower microbend losses

Fiber Parameters: Summary

- Introduced

- Fiber **core** and **cladding**
- Fiber **guiding properties**
 - » Total internal reflection
 - » Guiding by refractive index change (graded index)
- **Step-index** or **graded-index** fibers
 - » Both GI and SI can be modeled with power-law profile

- **Modes** in fibers

- » **Single-mode fiber**
 - **Mode field diameter (MFD)**
 - **Cutoff wavelength**
- » **Multimode fiber**
 - **V-parameter**
 - **Core radius, a**
 - **Numerical aperture, NA**

Fiber Parameters: Summary (cont.)

- **Multimode fibers**

- **Pro:**

- » **Moderate distances and/or data rates**
 - » **Easier coupling (larger core & NA)**

- **Con:**

- » **Lack extreme bandwidth capacity**
 - » **Mode mixing makes unpredictable behavior at joints**

- **Single-mode fibers**

- **Present fiber of choice**

- **Pro:**

- » **High data rate-distance combinations**
 - » **Lower fiber attenuation**

- **Con:**

- » **Lower fabrication tolerances**
 - » **Lower coupling efficiency**
 - » **Lower misalignment tolerance at joints**
 - » **Increased susceptibility to bending and spooling losses**

- **Costs:**

- **About equal**
 - **Readily available**

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Fiber Market Trends

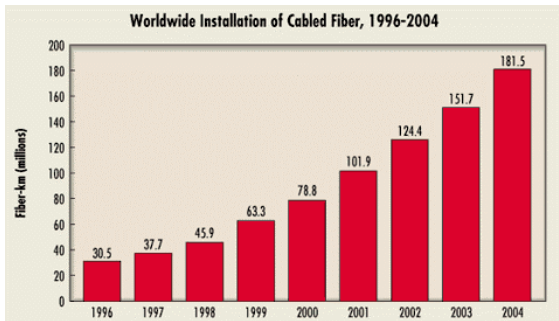


Figure 1. Worldwide demand for fiber-optic cable has increased deployment 38% in 1999 to 63.3 million km of cabled optical fiber, from 45.9 million km of fiber in 1998.

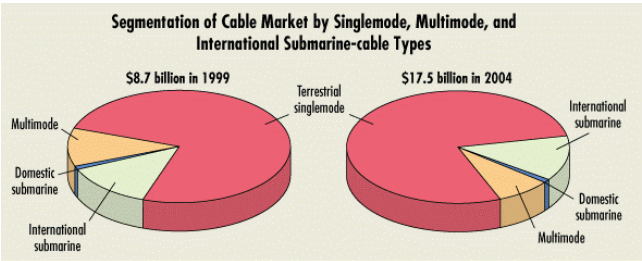


Figure 2. Segmentation of the cable market by terrestrial singlemode, multimode, international submarine, and domestic cable types.

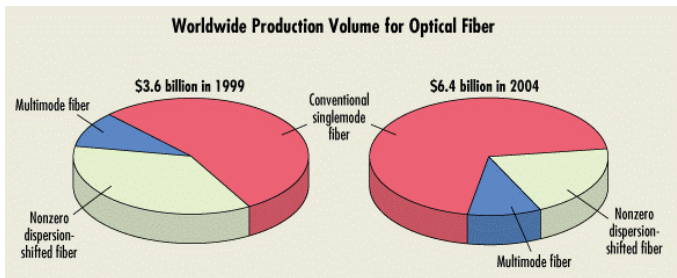


Figure 3. In 1999, demand for optical fiber was 70.2 million km of fiber, a \$3.6-billion market.